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Abundance of Atlantic salmon (*Salmo salar*) in the Stewiacke River, NS, from 1965 to 2002.

Abondance du saumon atlantique (*Salmo salar*) dans la rivière Stewiacke (N.-É.) entre 1965 et 2002.

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ABSTRACT

Atlantic salmon of the Stewiacke River, NS, are a part of a larger population assemblage, known as "inner Bay of Fundy Atlantic salmon" that were designated "endangered" by COSEWIC in 2001. Data for Stewiacke River salmon consist of catch-effort data from the recreational fishery (27 years), estimates of juvenile densities obtained by electrofishing (23 years), an index of adult abundance obtained by electrofishing by boat (10 years) and counts of adults bypassing a fence (4 years). Our purpose here is to use the data to estimate the number of adult salmon returning to the Stewiacke River from 1965 to 2001. We used maximum likelihood to model the catch-effort, juvenile electrofishing, adult electrofishing and fence count data to obtain estimates of the annual spawning run size during this time period. Results indicate a population size in the range of 1,100 to 6,700 during the late 1960's and early 1970's. Maximum likelihood estimates of the number of fish in the spawning run did not exceed 50 during the last 5 years, and are less than 10 since 1999. Markov chain Monte Carlo methods were used to derive Bayesian posterior distributions for the model parameters. The analyses indicate a 90% probability that the population has declined by more than 99.6% during the last 30 years and by more than 92% since the early 1990's. During the last 11 years, the estimated population size was less than during the preceding year in all but 4 years.

RÉSUMÉ

Les saumons atlantiques de la rivière Stewiacke (N.-É.) font partie d'un assemblage de populations connu sous le nom de « saumon atlantique de l'arrière-baie de Fundy ». En 2001, le COSEPAC a désigné cet assemblage comme étant « en voie de disparition ». L'information disponible sur le saumon de la rivière Stewiacke consiste en des données sur les prises et l'effort de pêche récréative (27 ans), des estimations de la densité de juvéniles obtenues par pêche électrique (23 ans), un indice de l'abondance d'adultes obtenu par pêche électrique à partir de bateaux (10 ans) et des données sur le nombre d'adultes qui franchissent une barrière (4 ans). La présente étude a pour objectif d'estimer la remonte annuelle de géniteurs dans la rivière Stewiacke entre 1965 et 2001 à partir de ces données en les modélisant par la méthode du maximum de vraisemblance. Les résultats montrent que la taille de la population se chiffrait entre 1 100 et 6 700 géniteurs à la fin des années 1960 et au début des années 1970. Les estimations de vraisemblance maximale de la remonte de géniteurs n'ont pas dépassé 50 au cours des cinq dernières années et sont inférieures à 10 depuis 1999. Nous avons utilisé les méthodes de la chaîne de Markov et de Monte Carlo pour déterminer les distributions bayesiennes à posteriori des paramètres du modèle. Les analyses montrent qu'il existe une probabilité à 90 % que l'effectif de la population ait chuté de plus de 99,6 % au cours des 30 dernières années et de plus de 92 % depuis le début des années 1990. Pour sept des onze dernières années, l'estimation de la taille de la population a baissé par rapport à l'année précédente.

INTRODUCTION

The Atlantic salmon of the Stewiacke River, NS, is part of a population assemblage designated "endangered" by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in May 2001. This assemblage, deemed "inner Bay of Fundy (iBoF) Atlantic Salmon" includes salmon native to rivers in the Bay of Fundy, north of the Saint John River, NB, and north of the Annapolis River, NS, exclusive of these rivers. Salmon are known to have occupied at least 32 rivers in this area (DFO 2003). Of these rivers, the Stewiacke River has the third largest area available for juvenile salmon production (Amiro et al., in review). The salmon population in this river, similar to many iBoF rivers, is comprised mostly of grilse and repeat-spawning grilse (Amiro 2003). Atlantic salmon from this river have been exploited both recreationally and commercially.

Our purpose is to use the data available for Stewiacke River salmon from 1965 to 2002 to estimate annual adult salmon returns and spawning escapements. These estimates enable us to examine the extent of the population decline since 1965. In so doing, we also provide annual estimates of the catch and harvest rates for the recreational fishery on this river. Additionally, we summarize information about salmon in this river that can be used to make inferences about changes in survival rates and productivity in this population.

METHODS

Approach

We developed a model to estimate the abundance of salmon in the Stewiacke River from 1965 to 2001, similar to that described by Rago (2001), and use the model to estimate the percent decline in abundance during this time period. Additionally we estimate recreational fishery catch and harvest rates from 1965 to 1990, after which the fishery was closed.

Fournier and Archibald (1982) and Deriso et al. (1985) developed a general theory for statistical catch-at-age models for stock assessment that allow auxiliary data to be incorporated. Although we are not using catch-at-age data, our approach is similar in that we use multiple indices (auxiliary data) together with catch and effort data to estimate abundance and harvest rates for this population. The core of the model is the basic catch equation for a type I fishery (Ricker 1975). Auxiliary data, in the form of counts at an adult fish monitoring fence, estimates of juvenile salmon densities in fresh water obtained by electrofishing and indices of adult salmon abundance in fresh water obtained by boat electrofishing are combined using a statistical model. The model is "anchored" using counts of the number of fish returning to the river in 1992 to 1995 at a monitoring fence calibrated by mark and recapture experiments in 1992 and 1993.

Data

The data used in this model are:

1. Recreational catch and effort (Table 1):

We used the recreational catch and effort data as indices of the number of large and small salmon returning to the river for the years 1965 to 1990 (the recreational fishery closed after 1990). The recreational catches of salmon are reported in the "Red Book" series (e.g. O'Neil et al. 1985) and are collated by Swetnam and O'Neil (1984), O'Neil and Swetnam (1984) and Swetnam and O'Neil (1985). Large salmon (63 cm or larger) and small salmon (less than 63 cm) were recorded separately. Numbers of fish harvested were those reported by Fishery Officers, 1965 to 1984, while the numbers released and harvested were estimated from Salmon License Stub returns from 1985 to 1990. Effort was estimated in rod days where any portion of a day fished by one angler was recorded as one rod day.

2. Boat Electrofishing (Table 2):

Abundance of adult salmon in the Stewiacke River was monitored from 1988 to 1998 (excluding 1994) by electrofishing by boat (Amiro and Jefferson 1997). We use the resulting catch and effort time series as indices of the annual spawning escapement after the fishery. The catch is reported with the size categories combined. Effort was reported as the kilometres of river covered while electrofishing on an annual basis.

3. Fence Counts and Mark-Recapture Experiments (Table 3):

A counting fence was operated on the Stewiacke River from 1992 to 1995. Partial counts were obtained in 1992 and 1993 and the population size estimated using mark and recapture methods (marking at the fence and recapture with the electrofishing boat). Counts were also obtained in 1994 and 1995. The numbers of large and small salmon passing by the fence were recorded annually.

4. Electrofishing (Table 4):

Densities of juvenile Atlantic salmon in the Stewiacke River were monitored by electrofishing in the years 1968, 1969, 1976, 1977, and 1984 to 2002. Between 4 and 44 sites were electrofished annually (>26 annually since 1984). Since 1984, electrofishing sites were selected using a stratified random design. Strata were defined using gradient (0.25% intervals) and distance from the mouth of the river (10 km intervals). Electrofishing sites were selected so that all strata were sampled in proportion to the amount of habitat available in each strata (Amiro et al. 1989; Amiro 1993). Although the selection of sites varied between years, efforts were made to ensure that all habitat types were representatively sampled. The number of salmon within a site was estimated using mark-recapture methods (Amiro et al. 1989), or when too few fish were captured, using the electrofishing catchability from the mark-recapture sites. We use the resulting densities as an index of egg deposition:

Number of age-0 salmon in year t is an index of egg deposition in year t-1.

Number of age-1 salmon in year t is an index of egg deposition in year t-2.

Number of age-2 salmon in year t is an index of egg deposition in year t-3.

Density dependent relationships with estimated egg depositions were initially assumed.

The Model

A schematic of the model is provided as Figure 1. Of primary interest are the number of fish in each size category, s, returning to the river to spawn in year t, denoted $N_{t,s}$. Information about the size composition of the population is not available for all years. We therefore estimate the number of fish returning to the river in each year, and the proportion of fish in each size category, assumed constant over years. This assumption is necessary because proportions cannot be estimated for years when size data are not available (i.e. post-1995).

The catch in each year and size category, $C_{t,s}$, is related to $N_{t,s}$ through the instantaneous rate of fishing mortality for each size class and year, denoted $F_{t,s}$:

$$C_{t,s} = N_{t,s}(1 - e^{-F_{t,s}}).$$

We assume that $F_{t,s}$ is proportional to the fishing effort in year t, E_t, and is related through the size-specific catchability coefficients q_s:

$$F_{t,s} = q_s E_t.$$

The proportion of the recreational catch that was retained averaged 0.824 for small salmon for the years 1983 to 1990 and was 0.758 for large salmon in 1983 (a catch and release policy was implemented for large salmon in 1984). These values were used as constants in this analysis, and used to estimate the number of fish harvested for the 1983 to 1990 time period for small salmon, and 1983 for large salmon. We assumed that, prior to 1983, all captured fish were harvested. This assumption was made because we do not have the data to estimate the proportion harvested for the earlier years. An alternative assumption, that these constants apply for all years, is examined in the section on robustness. For the later time period, the number of fish harvested in each size class in each year, $H_{t,s}$, was estimated as $C_{t,s}$ times the proportion harvested in each size class. Escapement in each year and size class, $Esc_{t,s}$, is then;

$$Esc_{t,s} = N_{t,s} - H_{t,s}.$$

$Esc_{t,s}$ is not corrected for hook and release mortality or bias resulting from multiple captures of the same fish in a catch and release fishery.

The counts of salmon returning to the river as measured at the Stewiacke River counting fence were assumed complete in 1994 and 1995, but not in 1992 and 1993. The 1992 and 1993 counts were adjusted upwards using the mark and recapture experiments carried out in those years. The fence count in size category s and year t, $Fence_{t,s}$, is then equal to the number of fish returning to the river in each size category and each year:

$$Fence_{t,s} = N_{t,s}.$$

The number of fish captured when electrofishing for adults with the boat is reported for size categories combined. The relationship between the number captured by boat electrofishing in year t, $C_{\text{boat},t}$, and $Esc_{t,s}$ is similar to that for the recreational catch:

$$C_{\text{boat},t} = (1 - e^{-q_{\text{boat}} E_{\text{boat},t}}) \sum_s Esc_{t,s},$$

where q_{boat} is the catchability coefficient for the boat electrofishing for adults, and $E_{\text{boat},t}$ is the elecrofishing effort in year t.

Egg deposition in year t, $Eggs_t$, was calculated as product of $Esc_{t,s}$ and the size class specific fecundity, fec_s, summed over size classes:

$$Eggs_t = \sum_s Esc_{t,s} fec_s$$

We estimated the fecundity of Stewiacke River salmon from the data in Table 3 of Amiro (1990), as the mean fecundity of large and small salmon weighted by the sex ratio in each group. These values, 2,364 eggs per small salmon, and 7,545 eggs per large salmon, were used as constants in this analysis.

We use the notation $P_{t,a}$ to denote the mean density of juvenile salmon of age a in year t (we are using P for parr, and do not distinguish between age-0 parr and fry). Three ages of parr are included in the model: ages 0 to 2. We assumed a density dependent relationship between egg deposition and the resulting number of fish in that cohort. The Beverton-Holt and Ricker models are the most commonly used two parameter spawner-recruit (SR) models (Hilborn and Walters 1992), and are appropriate candidates for the density dependent functional model. These models differ fundamentally in their assumptions of the underlying biology, the latter showing a decline in recruitment at higher spawner abundance, a phenomenon known as overcompensation. As a result of this characteristic, a one-to-one relationship between the number of age-a parr in year $t+a$ and the egg deposition in year t does not exist for the Ricker model. Therefore, the Ricker functional form is not suitable for this analysis and we used the Beverton-Holt model. The Beverton-Holt model also has the advantage that the asymptotic recruitment level can be rescaled and interpreted as an estimate of carrying capacity (Myers et al. 2001, Gibson and Myers 2003). However it often provides estimates of the slope at the origin that are higher than those from the Ricker model (Myers et al. 1999). For each age category, we estimated the asymptotic recruitment level, R_{0a}, and the slope at the origin, α_a, for this model:

$$P_{t,a} = \frac{\alpha_a Eggs_{t-a-1}}{1 + \frac{\alpha_a Eggs_{t-a-1}}{R_{0a}}}.$$

Initial model runs indicated that R_0 was not well determined for age-0 fish. R_0 was always estimated as the upper bound placed on the parameter, as would occur if a linear function

were more appropriate (a linear relationship between egg deposition and age-0 density would be appropriate if electrofishing occurred prior to density dependent processes within the cohort). In the final model, a linear function was used for age-0 fish:

$$P_{t,0} = \alpha_0 Eggs_{t-1}$$

Parameter estimates were obtained by minimizing an objective function (*O.B.V.*) that is the sum of the negative log likelihoods (Quinn and Deriso 1999) for the catch (ℓ_{catch}), the fence counts (ℓ_{fence}), the boat electrofishing catch (ℓ_{boat}) and the juvenile electrofishing data ($\ell_{electrofishing}$). The relative contribution of each likelihood to the objective function was controlled using a set of weighting values, λ_i. These values may be selected to keep any one part of the objective function from dominating the fit, or alternatively, to reflect perceptions of data accuracy (Merritt and Quinn 2000). Here, we set all weights equal to one, an approach that has the advantage that the *O.B.V.* can be interpreted as the likelihood. We used lognormal error structures for all likelihoods. Superscripting observed values with "obs", the log likelihoods are:

1. Recreational Catches:

$$\ell_{catch} = -n\ln(\sigma_{catch\,s})\sqrt{2\pi} - \sum_{t,s}\ln(C_{t,s}^{obs}) - \frac{1}{2\sigma_{catch\,s}^2}\sum_{t,s}(\ln C_{t,s}^{obs} - \ln C_{t,s})^2$$

2. Fence Counts:

$$\ell_{fence} = -n\ln(\sigma_{fence})\sqrt{2\pi} - \sum_{t,s}\ln(Fence_{t,s}^{obs}) - \frac{1}{2\sigma_{fence}^2}\sum_{t,s}(\ln Fence_{t,s}^{obs} - \ln Fence_{t,s})^2$$

3. Electrofishing (log likelihoods were calculated separately for each age class and then summed):

$$\ell_a = -n\ln(\sigma_a)\sqrt{2\pi} - \sum_{t}\ln(P_{t,a}^{obs}) - \frac{1}{2\sigma_a^2}\sum_{t}(\ln P_{t,a}^{obs} - \ln P_{t,a})^2$$

$$\ell_{electrofishing} = \sum_{a}\ell_a$$

4. Boat Electrofishing:

$$\ell_{boat} = -n\ln(\sigma_{boat})\sqrt{2\pi} - \sum_{t}\ln(C_{boat,t}^{obs}) - \frac{1}{2\sigma_{boat}^2}\sum_{t,s}(\ln C_{boat,t}^{obs} - \ln C_{boat,t})^2$$

In these equations, n is the sample size for the corresponding data set and σ_x is the corresponding shape parameter (for a lognormal distribution, σ is the standard deviation of a normal distribution prior to exponentiation).

Initial attempts to estimate the σ's for all model components, and for all components except for the fence count, were unsuccessful. Therefore, we used σ's estimated for other Atlantic salmon populations for the juvenile electrofishing component of the model. Myers et al. (1995) published spawner-recruit relationships for 15

populations and recruitment age categories for Atlantic salmon. For a recruitment age of 1, σ averaged 0.330 (n = 4; range: 0.293 to 0.402). Models were fit to single data sets for recruitment ages of 0 and 2, for which σ was estimated as 0.334 and 0.581 respectively. These estimates were similar to the estimated σ's when smolt was used as the recruitment category (mean=0.329; n=5; range: 0.206 to 0.440). Based on their analyses, we set σ_a equal to 0.334 for a=0, 0.330 for a=1 and 0.580 for a=2. σ_{fence} was set equal to 0.1 to reflect a higher degree of certainty about the fence count data. The robustness of the results to this assumption was evaluated estimating σ_{fence} with the model. For the remaining model components (the recreational fishery and boat electrofishing), an estimate of σ was calculated within the model as:

$$\hat{\sigma} = \sqrt{\frac{1}{n}\sum \log\left(\frac{obs_i}{pred_i}\right)^2},$$

and substituted into the likelihood equation. Here, obs_i and $pred_i$ are the observed data and predicted values associated with each model component and n is the sample size.

The objective function is:

$$O.B.V. = -(\lambda_1 \ell_{fence} + \lambda_2 \ell_{catch} + \lambda_3 \ell_{electrofishing} + \lambda_4 \ell_{boat}).$$

We set up the model to estimate the log of the total escapement in each year (37 parameters), the average proportion of the population that are small salmon (1 parameter), the catchability coefficients for the recreational fisheries and boat electrofishing (3 parameters), the slope at the origin and asymptotic level for age-1 and age-2 egg SR models (4 parameters) and the slope at the origin for the age-0 SR model. We programmed this model using AD Model Builder (Fournier 1996). AD Model Builder (ADMB) uses the C++ auto-differentiation library for rapid fitting of complex non-linear models, has Bayesian and profile likelihood capabilities, and is designed specifically for fitting these types of models.

Bayesian Analyses

Bayesian methods provide a powerful tool for assessing uncertainty in fisheries models (McAllister et al. 1994). Punt and Hilborn (1997) and McAllister and Kirkwood (1998) have reviewed their fisheries applications. The posterior probability distributions resulting from Bayesian analyses show the uncertainty in model or policy parameters including both estimation uncertainty as well as prior information about their values (Walters and Ludwig 1993). ADMB uses a Markov Chain Monte Carlo (MCMC) algorithm (Carlin and Louis 1996) to approximate the posterior distribution for parameters of interest. MCMC is a stochastic simulation method used to evaluate complex integrals in order to derive posterior distributions. ADMB uses the Metropolis Hastings algorithm (Chib and Greenberg 1995) to generate the Markov chain, using a multivariate normal distribution based on the variance-covariance matrix for the model parameters as the proposal function. If the chain is long enough, the posteriors will be reasonably well approximated.

We assumed uniform bounded priors for all model parameters. Bounds were wide enough not to influence the fit. We used 1,000,000 iterations after a burn in of 100,000 iterations, and sampled every 1,000th iteration to derive the posterior distribution. This level of thinning was sufficient to ensure that autocorrelation in the chain was not problematic.

Diagnostics

Whenever minimization is used to estimate parameters in a nonlinear model, there is a possibility of convergence to a local minimum, rather than the global minimum. We ran many iterations of the model using several starting values and within limits, the estimates are robust with respect to the starting values. We also examined the sensitivity of the results to the weighting of model components and changes in model formulation. These included:

1. Increasing the fence count λ's to 100. This forces the model to fit to the observed fence counts very closely and is the equivalent of assuming they are known without error.
2. Decreasing the age-0 electrofishing λ to 0.01. This is nearly the equivalent to not including the age-0 electrofishing data in the model.
3. Decreasing the age-2 electrofishing λ to 0.01. This is nearly the equivalent to not including the age-2 electrofishing data in the model.
4. Decreasing the age-0 and age-1 electrofishing λ's to 0.01.
5. Decreasing the recreational fishing λ's to 0.01. In this case the influence of the recreational fishing data is very low relative to the other data sets.
6. Increasing the recreational fishing λ's to 100. In this case the influence of the recreational fishing data is very high relative to the other data sets.
7. Removing the boat electrofishing for adults from the model.
8. Items 2, 3 and 7 combined.
9. Increasing the age-1 electrofishing λ to 100.
10. Changing the assumption about catch and release practices in the 1965 to 1983 time period such that 17.6 % of small salmon and 24.2 % of large salmon that were caught were released (all were retained in the base model).
11. Estimating σ_{fence} within the model.

Convergence of the Markov chain was inferred informally by comparing the similarity of the 10th and 90th percentiles of the posterior densities based on the first 500,000 iterations with those based on the second 500,000 iterations, and by comparison of the posterior densities from several chains (Gamerman 2000).

RESULTS

Between 1965 and 1990, fishing effort for Atlantic salmon on the Stewiacke River varied from a low of 220 rod days in 1965 to 9,269 rod days in 1983 (Figure 2). During these years, observed catches of small salmon varied between a low of 14 fish in 1965 to a high of 1,649 fish in 1983. Catches of large salmon varied between 39 fish in

1965 and 580 fish in 1986. The fit of the predicted to observed catch of small and large salmon is similar (Figure 2), with large outliers in 1983. The maximum likelihood estimate (MLE) of the proportion of small salmon in this population was 0.61 (Table 5).

Parameter estimates from the model are provided in Table 5. The log of the catchability coefficients for the recreational fishery were higher for small salmon (-8.806) than for large salmon (-9.239). These estimates suggest that at a fishing effort of 3,000 rod days, 36.2% of the small salmon and 25.3% of large salmon would be captured by the recreational fishery. Posterior probability densities for the log of the recreational fishery are relatively wide (Figure 3). The 10^{th} and 90^{th} percentiles of the posterior density for the log of the catchability for large salmon are –9.717 and -8.905, implying an 80% Bayesian credible interval (BCI) for the catch rate at an effort of 3,000 rod days of 16.5 to 33.4%. Similarly, the 80% credible interval for the catch rate for small salmon at an effort of 3,000 rod days is 26.0 to 44.1%. Posterior probability densities for the annual catch rates are provided in Appendix 1.

The logarithm of the boat electrofishing catchability for adults was -8.047 (Table 5, Figure 4). At an electrofishing effort of 40 km, this estimate implies an expected catch of 1.3% (80% BCI = 0.05 to 3.4%). The predicted boat electrofishing catch matches the observed catch reasonably well, with the exception of a large residual in 1991 (Figure 5).

Densities of juvenile salmon in the Stewiacke River have been determined by electrofishing in 23 years since 1968. The densities of juvenile salmon show a gradual decline through the 1990's (Figure 6). The densities predicted by the model track the observed densities reasonably well (Figure 7) with the exception of two years in the mid-eighties (age-1) and the mid-eighties and early 1990's (age-2 parr). The functional relationships between egg deposition and subsequent juvenile densities are shown in Figure 8. The asymptotic levels for age-1 and -2 densities are 23.9 and 7.4 fish per 100 m^2 (Figure 8; Table 5). The posterior probability densities for these parameters (Figure 9) show that the data do not preclude the possibility that the asymptotic recruitment levels for age-1 and age-2 salmon could be higher (90^{th} percentiles of 30.1 and 25.8 fish per $100m^2$ for age-1 and age-2 fish respectively).

Time series of the MLE's of the numbers of salmon returning to the river are shown in Figure 10. Based on these estimates, the number of salmon returning to the river (before the recreational fishery and after the commercial fishery) peaked in 1967 at 6,693 salmon (80% BCI = 4,698 to 10,998). The MLE's of the number of salmon returning to the river have not exceeded 50 fish since 1996, and have not exceeded 500 fish since 1991. Posterior probability densities for the number of returning salmon annually are provided in Appendix 1. The 90^{th} percentiles of the posterior probability density for the number of returns in years 1999 to 2001 are all less than 10 fish (Table 6).

The recreational harvest rates for large and small salmon are shown in Figure 11. The MLE's of the annual exploitation rates show the highest rate in 1979 at 66.0% for small salmon and 50.3% for large salmon. The MLE's of the annual exploitation rates remained below 36% for small salmon from 1965 to 1976 (Figure 11), and below 25%

for large salmon during this time period. The increase in estimated catch and exploitation rates during the late 1970's and early 1980's results from increased fishing effort during this time period.

We estimated the percent decline in population size for 5-, 10-, 20- and 30-year time periods. To reduce the effect of large or small year classes, we estimated the mean number of fish returning to the river for the five-year time periods: 1997-2001, 1992-1996, 1987-1991, 1977-1981 and 1967-1971. Percent decline was calculated as the complement of the ratio of the 1997-2001 mean to the other means, converted to a percentage. The MLE of the mean population size for the 1997-2001 time period was 13 salmon, in comparison with 169 salmon for the 1992-1996 time period, 1,025 salmon for the 1987-1991 time period, 1,325 salmon for the 1977-1981 time period and 3,171 salmon for the time period from 1967-1971 (Table 5). MLE's for the percent decline are 92% for the 5-year comparison, and 98.8% for the 10-year comparison, and greater than 99% for the 20-year and 30-year comparisons (Figure 12). The posterior probability densities for the percent decline indicate a 90% probability that the mean population size for the 1997-2001 time period was less than 6% its mean size during years 1992 to 1999, and a 90% probability that the five-year mean population size has declined by more than 99.6% over the last 30 years.

Although the Stewiacke River salmon population shows an overall decline in size at least since the 1970's, population size has been variable. Examination of the ratio of the population size in year t to the size in year t-1 (Figure 13), indicates that between 1966 and 1989, the population size was larger than it was in the previous year about half of the time (13 of the 24 years), although the overall trend was downward. From 1990 to 2001, the estimated population was less than the population size in the previous year in 7 of the 12 years.

Summaries for eleven alternate model runs are shown in Table 7. When the age-1 electrofishing is weighted higher than the other electofishing data sets (runs 2,8 and 9), the mean 1997 - 2001 population size estimates are higher than for the other runs, while the estimates for the 1960's and 1970's are lower. The high mean population size for the 1997-2001 time period from this model run is derived almost entirely from an estimated larger return of salmon in 2000 (estimated returns for other years in the time period are low). The 2000 estimate is based on the 2002 electrofishing age-1 density, which may not be indicative of wild production because of the captive-reared fry that were released into the watershed in 2000. When the recreational fishery component of the model is heavily weighted (run 6), unrealistically high estimates of the population size are obtained for the 1992 - 1996 time period. Additionally, recreational harvest rates exceed 85% in some years in this model run, another unrealistic estimate. Therefore, we concluded that the base model was the most parsimonious of these model runs.

The commercial salmon catch was not included in the model due to uncertainty about the proportion of the fish taken in the fishery that were native to the Stewiacke River. This fishery is executed in the upper Minas Basin and the catch is reported in Fishery Statistical Districts 42 and 43, which includes other rivers. Landings are

available for the time period from 1967 to 1984. During the time period, the reported landings in these districts were highest in 1968 (2,224 fish), and show a general decline until the closure of the fishery in 1985 (Figure 14). A comparison of the number of Stewiacke River salmon that would have escaped this fishery with the reported landings is provided in Table 8. Without an assumption about the proportion of the landings that are native to the Stewiacke River, exploitation rates cannot be calculated for this fishery. Assuming all fish caught in the commercial fishery are native to the Stewiacke River ensures overestimation of the exploitation rates, and suggests that exploitation rates varied between 10 and 67% through this time period. If 50% of the fish were native to the Stewiacke River, exploitation rates would have been in the range of 5 to 51%.

DISCUSSION

In this document we have provided estimates of the number of fish returning to the Stewiacke River, NS, annually from 1965 to 2001, and used these results to estimate the percent decline in the population during this time period. We have also estimated the catch and harvest rates for the recreational fishery on this river during this time period. Overall the results suggest a probability of 0.9 that the population decline is greater than 99.6% during this time period.

Several assumptions were made when setting up the model, and when possible, were chosen to provide conservative estimates of the percent decline in this population. One exception is the assumption that recreational fishers kept all fish prior to 1983. Fishers released 17.6% of small salmon during the 1983 to 1990 time period and released 24.2% of large salmon in 1983. If fishermen released some portion of fish prior to 1983, the escapement estimates would have been higher during this time period. Through the relationship between escapement and juvenile density, this could potentially increase the spawner escapement estimates in the 1990's. The model run with the assumption that 17.6% of small salmon and 24.2% of large salmon were released in all years prior to the implementation of the catch-and-release regulation produced slightly lower estimates of population size in the 1960's and 1970's. The estimated percent declines from this model run still exceeded 99%.

We did not include the commercial fishery in the model. Catches of Stewiacke River salmon are reported for Fishery Statistical Districts 42 and 43. These catches include salmon returning to other rivers in these districts. The commercial salmon fishery was closed in 1985. Given that the fishery was open during the first part of the time series, but not the latter part of the series, the effect of its exclusion from the model would be to underestimate the true extent of the decline in this population.

Another key assumption within this model is that the instantaneous rate of fishing mortality is proportional to effort. Peterman and Steer (1981) found that, in Pacific salmon recreational fisheries, catchability increased as abundance of salmon decreased. They attributed this phenomenon in part to the restricted environments in which fish are found, which combined with communication among fishers, could lead to concentrated effort on spatially localized fish stocks. If a similar pattern exists in iBoF salmon

recreational fisheries, the effect would be to underestimate the true decrease in abundance in these populations.

Rago (2001) provided a test of index based assessment models for Atlantic salmon by comparing output from a catch-effort model with a single index (fry density) with abundance and exploitation rate estimates obtained using other methods. Using data from the Miramichi River, Rago (2001) found that when no other estimates of exploitation rates or abundance were available, the model output was not in agreement with the estimates obtained using other methods, and concluded the method was unreliable. However, when another estimate of abundance was available for a single year, model agreement was much better. When other estimates of abundance were available for three years, model agreement was quite good. For the Stewiacke River, we had four years of data (fence counts) with which to "anchor" the model coefficients, although the four years do not span the range of estimated abundance. Additionally, we used four other indices plus the catch to estimate abundance, rather than a single index.

The estimated slopes at the origin for the egg deposition-juvenile density relationships were lowest for age-2 parr and highest for age-1 parr. In standard interpretations of density dependent models, the youngest age should have the highest slope at the origin. The pattern exhibited here could arise if age-0 fish are underrepresented in the sampling, either as a result of selectivity of the sampling gear or a contagious distribution of age-0 fish. Because the densities are being used as indices of abundance, the pattern is not problematic, as long as the process generating the pattern (e.g. selectivity) is stationary throughout the data collection period.

The time periods selected for estimating declines (5, 10, 20 and 30 year comparisons of 5-year mean population size) were chosen to compare population size on the scale of decades. As a result of this decision, the highest abundances in the 1970's and 1980's (1974 and 1983) are not included in the comparisons. Had the time periods been selected to include these years, the estimated percent decline would have been even greater.

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Table 1. Recreational catch (number of fish) of small and large Atlantic salmon in the Stewiacke River, 1965 to 1993. Effort is reported in rod days. The number of fish harvested by the fishery is recorded after 1982.

	Small Salmon		Large Salmon		
Year	Catch	Harvested	Catch	Harvested	Effort
1965	14		39		220
1966	241		47		901
1967	452		389		2400
1968	185		179		1950
1969	48		62		838
1970	355		163		2160
1971	337		46		1357
1972	343		265		2347
1973	520		224		2954
1974	1087		355		2310
1975	442		180		1150
1976	940		198		2070
1977	104		370		4240
1978	545		75		2300
1979	681		239		7200
1980	41		203		3520
1981	531		89		2852
1982	307		97		4655
1983	1649	1371	331	251	9269
1984	425	338	141	13	5215
1985	1038	829	361	0	5955
1986	495	429	580	0	6190
1987	148	114	215	0	3319
1988	207	185	75	0	2804
1989	1157	946	184	0	5057
1990	151	124	35	0	2285
1991	6	0	0	0	19
1992	1	0	0	0	3
1993	2	0	0	0	9

Table 2. Number of adult Atlantic salmon captured by electrofishing with a boat on the Stewiacke River, NS, from 1988 to 1998. Effort is reported as the length of river electrofished (km) annually. C.P.U.E. is the number of salmon captured per kilometer of river that was electrofished.

Year	Catch	Effort	C.P.U.E.
1988	23	31.8	0.72
1989	19	35.2	0.53
1990	4	35.2	0.11
1991	58	111.5	0.52
1992	12	43.11	0.27
1993	9	123.3	0.07
1994		0	
1995	3	82.2	0.03
1996	8	82.2	0.10
1997	0	41.1	0.00
1998	1	41.1	0.02

Table 3. Number of large and small Atlantic salmon counted at the Stewiacke River, NS, counting fence from 1992 to 1995, and the number of salmon that were marked (M), captured and examined for marks (C) and were marked-recaptures (R) during mark-recapture experiments in 1992 and 1993. Marking occurred at the fence and the recapture phase was conducted with the electrofishing boat.

	Number Counted at the Fence		Mark – Recapture Experiments		
Year	Small	Large	M	C	R
1992	54	123	177	12	9
1993	320	47	225	8	5
1994	211	10			
1995*	6	44			

* includes 7 aquaculture escapes of unknown origin

Table 4. Means and standard deviations of age-0, age-1 and age-2 densities (number/100m^2) of Atlantic salmon in the Stewiacke River, NS, estimated during electrofishing surveys from 1968 to 2002. "N" is the number of sites electrofished in each year. Distinctions were not made between age-1 and age-2 parr in pre-1980 surveys and all age-1 and older parr are reported here as age-1 for that period.

		Age-0		Age-1		Age-2	
Year	N	mean	s.d.	mean	s.d.	mean	s.d.
1968	11	106.6	76.7	23.8	30.3		
1969	9	72.1	82.6	22.5	15.5		
1976	4	13.9	8.0	24.3	9.5		
1977	21	37.3	28.8	13.2	9.3		
1984	44	45.9	47.0	17.0	13.2	6.8	7.9
1985	27	12.1	14.6	28.9	26.7	6.9	8.4
1986	38	26.8	30.7	16.0	13.0	8.2	9.0
1987	36	16.8	21.0	33.6	44.7	5.5	4.8
1988	29	16.9	23.1	18.5	9.0	7.0	5.2
1989	31	21.2	21.4	16.5	14.7	6.3	5.3
1990	31	18.7	28.2	19.7	16.7	3.3	3.2
1991	31	8.4	10.2	12.3	10.2	4.1	3.2
1992	37	14.9	24.4	15.0	12.2	2.0	2.1
1993	35	1.3	3.9	12.6	14.1	2.5	2.5
1994	35	9.7	11.8	2.9	2.6	3.7	4.2
1995	30	3.9	6.6	6.5	6.7	1.7	1.3
1996	35	1.2	2.7	5.3	4.9	1.9	1.7
1997	31	7.2	12.3	1.4	2.1	2.1	2.1
1998	37	1.5	4.2	1.9	2.3	0.3	0.5
1999	32	2.1	8.6	0.7	1.1	0.7	1.0
2000	33	0.0	0.0	0.5	0.8	0.3	0.4
2001	35	0.0	0.0	0.1	0.3	0.1	0.2
2002	40	0.0	0.3	2.5	7.9	0.1	0.2

Table 5. Parameter estimates for Stewiacke River Atlantic salmon obtained from the assessment model.

Parameter	Year	Estimate	Standard Error
Coefficients:			
log boat electrofishing q		-8.0473	0.6675
log recreational fishing q (small)		-8.8056	0.2312
log recreational fishing q (large)		-9.2391	0.2886
log alpha (age-0)		-12.3800	0.1451
log alpha (age-1)		-11.2600	0.2007
R0 (age1)		23.9190	3.7883
log alpha (age-2)		-12.7620	0.3126
R0 (age2)		7.4430	2.8235
proportion small salmon		0.6121	0.0168
Abundance Estimates:			
log(small + large escapement)	1965	7.3861	0.7909
log(small + large escapement)	1966	7.7006	0.6484
log(small + large escapement)	1967	8.4963	0.3401
log(small + large escapement)	1968	8.0618	0.3417
log(small + large escapement)	1969	6.8969	0.7522
log(small + large escapement)	1970	7.4010	0.7244
log(small + large escapement)	1971	7.3226	0.7143
log(small + large escapement)	1972	7.5046	0.7412
log(small + large escapement)	1973	7.3882	0.7282
log(small + large escapement)	1974	8.3337	0.6951
log(small + large escapement)	1975	6.8936	0.3329
log(small + large escapement)	1976	7.7063	0.3333
log(small + large escapement)	1977	6.2764	0.8432
log(small + large escapement)	1978	7.2174	0.7180
log(small + large escapement)	1979	6.3775	0.7574
log(small + large escapement)	1980	5.7292	0.8607
log(small + large escapement)	1981	7.1527	0.6510
log(small + large escapement)	1982	6.6160	0.5086
log(small + large escapement)	1983	7.7196	0.3241
log(small + large escapement)	1984	6.5834	0.3073
log(small + large escapement)	1985	7.4300	0.3145
log(small + large escapement)	1986	6.9479	0.3202
log(small + large escapement)	1987	6.7791	0.3258
log(small + large escapement)	1988	6.9959	0.3179

Table 5 (con't.). Parameter estimates for Stewiacke River Atlantic salmon obtained from the assessment model.

Parameter	Year	Estimate	Standard Error
log(small + large escapement)	1989	6.8651	0.3354
log(small + large escapement)	1990	6.1758	0.2962
log(small + large escapement)	1991	6.4692	0.3262
log(small + large escapement)	1992	5.3679	0.0695
log(small + large escapement)	1993	5.8811	0.0696
log(small + large escapement)	1994	4.5948	0.0691
log(small + large escapement)	1995	3.5235	0.0690
log(small + large escapement)	1996	4.9303	0.2980
log(small + large escapement)	1997	3.3595	0.2681
log(small + large escapement)	1998	3.3489	0.2663
log(small + large escapement)	1999	-0.9662	0.2761
log(small + large escapement)	2000	1.4367	0.2773
log(small + large escapement)	2001	0.8955	0.3708
Derived Parameters:			
a) mean N (1997-2001)		12.8	2.6
b) mean N (1992-1996)		168.8	10.7
c) mean N (1987-1991)		1,025.1	183.7
d) mean N (1977-1981)		1,324.9	474.1
e) mean N (1967-1971)		3,171.5	743.6
ratio: a/b		0.0762	0.0146
ratio: a/c		0.0125	0.0028
ratio: a/d		0.0097	0.0037
ratio: a/e		0.0041	0.0011

Table 6. Percentiles of the posterior probability density for the number of Atlantic salmon returning to the Stewiacke River, NS, from 1965 to 2001.

	Percentile								
Year	10%	20%	30%	40%	50%	60%	70%	80%	90%
1965	586	841	1,106	1,397	1,696	2,181	2,809	3,940	6,186
1966	1,187	1,535	1,965	2,358	2,836	3,437	4,354	5,696	8,131
1967	4,698	5,456	6,029	6,594	7,192	7,800	8,483	9,617	10,998
1968	2,895	3,340	3,696	4,088	4,407	4,729	5,165	5,754	6,769
1969	382	595	754	969	1,172	1,448	1,825	2,411	3,700
1970	823	1,222	1,565	1,924	2,373	2,894	3,717	4,980	7,364
1971	639	861	1,172	1,556	1,904	2,290	2,932	3,906	5,690
1972	919	1,422	1,820	2,278	2,752	3,403	4,260	5,495	7,713
1973	861	1,258	1,628	2,013	2,550	3,122	3,837	5,118	7,271
1974	2,422	3,196	4,147	5,039	5,982	7,439	9,367	12,196	18,015
1975	714	822	910	993	1,085	1,185	1,280	1,398	1,600
1976	1,834	2,104	2,390	2,630	2,841	3,095	3,381	3,812	4,472
1977	340	505	653	811	1,009	1,237	1,556	2,118	3,244
1978	663	966	1,298	1,580	1,960	2,458	3,224	4,148	6,124
1979	538	757	1,004	1,243	1,530	1,830	2,329	3,107	4,653
1980	166	252	352	461	581	720	945	1,199	1,934
1981	891	1,173	1,403	1,670	2,000	2,424	3,015	3,733	5,230
1982	808	1,031	1,204	1,376	1,567	1,800	2,124	2,565	3,491
1983	3,454	3,951	4,417	4,744	5,193	5,648	6,306	6,959	7,932
1984	765	846	920	998	1,080	1,177	1,277	1,403	1,603
1985	1,834	2,056	2,260	2,451	2,666	2,873	3,143	3,495	4,019
1986	1,109	1,273	1,406	1,537	1,651	1,789	1,937	2,131	2,441
1987	756	876	971	1,051	1,126	1,230	1,348	1,506	1,721
1988	941	1,051	1,157	1,264	1,343	1,462	1,591	1,754	2,036
1989	888	1,017	1,138	1,234	1,331	1,439	1,576	1,735	2,025
1990	400	450	493	533	576	618	669	733	843
1991	452	525	586	639	691	747	810	898	1010
1992	196	202	206	211	215	218	222	227	234
1993	326	338	345	351	358	364	372	381	392
1994	91	94	96	98	99	101	103	105	108
1995	31	32	33	33	34	35	35	36	37
1996	101	112	123	133	143	156	168	182	210
1997	21	23	25	28	29	32	34	37	42
1998	21	24	25	27	29	31	34	36	40
1999	0	0	0	0	0	0	0	0	1
2000	3	3	4	4	4	4	5	5	6
2001	2	2	2	2	2	3	3	3	4

Table 7. Summary of the 5-year mean number of fish returning to the Stewiacke River, and 5-year and 30-year percent declines in population size for several alternative model runs. Model run numbers correspond to the numbers listed in the Methods.

	Mean Number of Fish					Percent Decline	
Model Run	1997 - 2001	1992 - 1996	1987 - 1991	1977 - 1981	1967 - 1971	5 year	30 year
1. fence count λ's = 100	13	169	1,022	1,317	3,151	92.5	99.6
2. age-0 electrofishing $\lambda = 0.01$	21	153	781	1,001	1,396	86.3	98.5
3. age-2 electrofishing $\lambda = 0.01$	14	173	1,069	1,260	3,150	91.8	99.6
4. 2 and 3 above combined	model does not converge						
5. rec. fishing λ's = 0.01	13	170	1,039	2,810	3,923	92.1	99.7
6. rec. fishing λ's = 100	7	698	944	1,433	1,254	99.0	99.6
7. boat electrofishing removed	13	168	1,019	1,329	3,184	92.1	99.6
8. 2, 3 and 7 combined	21	152	819	942	1,342	86.3	98.5
9. age-1 electrofishing $\lambda = 100$	26	135	988	1,277	2,355	89.0	99.0
10. catch-release assumption changed	13	168	1,023	1,274	3,003	92.5	99.6
11. fence σ's estimated	16	203	1,169	1,550	3,728	92.4	99.6
Base Model	**13**	**169**	**1,025**	**1,325**	**3,171**	**92.4**	**99.6**

Table 8. A comparison of the reported commercial catch in Districts 42 and 43 with the escapement (from the commercial fishery) to the Stewiacke River from 1967 to the closure of the fishery in 1985. Exploitation rates (u) cannot be calculated without knowing the proportion of the catch that was native to the Stewiacke River. Rates below are calculated using the assumptions that 50% and 100% of the catch were salmon returning to the Stewiacke River.

Year	Catch (Number of Fish)	Number returning to the River	u (assuming 100% of Catch from the Stewiacke R.)	u (assuming 50% of Catch from the Stewiacke R.)
1967	733	6,693	0.10	0.05
1968	2,224	4,086	0.35	0.21
1969	1,002	1,103	0.48	0.31
1970	1,489	2,169	0.41	0.26
1971	1,475	1,806	0.45	0.29
1972	1,575	2,465	0.39	0.24
1973	620	2,376	0.21	0.12
1974	1,224	5,622	0.18	0.10
1975	1,252	1,145	0.52	0.35
1976	1,464	2,909	0.33	0.20
1977	1,153	926	0.55	0.38
1978	998	1,839	0.35	0.21
1979	1,304	1,519	0.46	0.30
1980	1,012	487	0.67	0.51
1981	991	1,853	0.35	0.21
1982	490	1,374	0.26	0.15
1983	597	5,203	0.10	0.05
1984	285	1,081	0.21	0.12

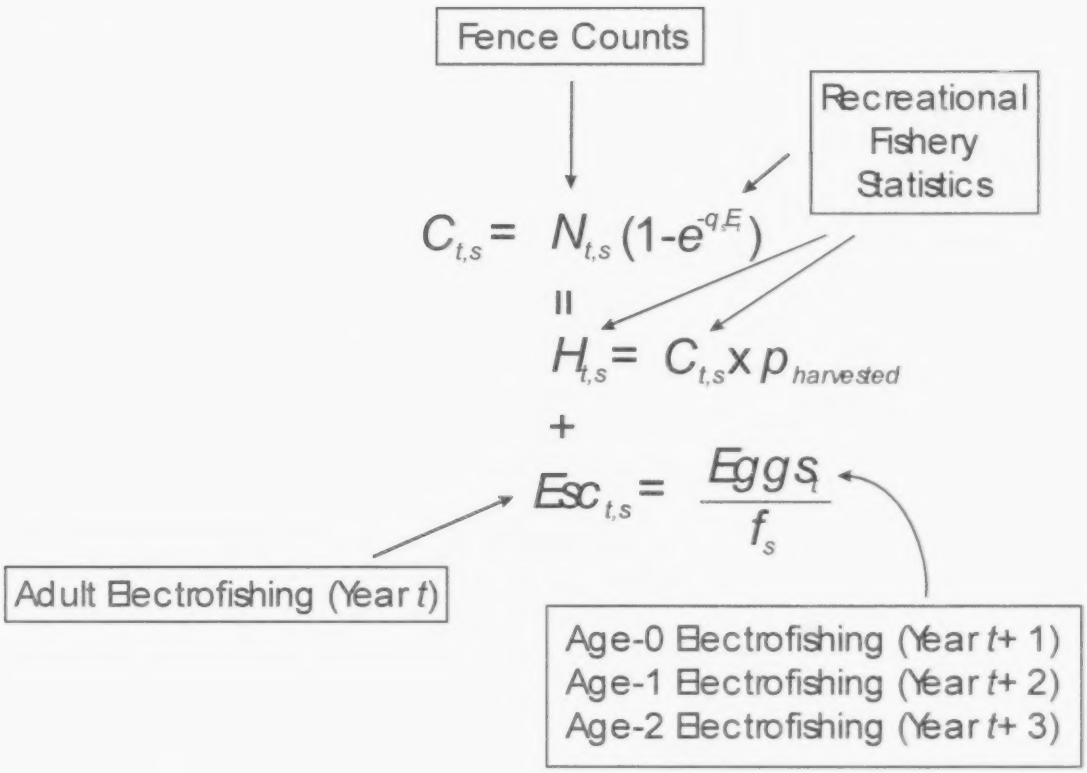

Figure 1. Schematic of model used to estimate abundance of Atlantic salmon in the Stewiacke River, NS. Data are shown in boxes and are used as indices of variables identified with the arrows. Notation and further model details are provided in the text.

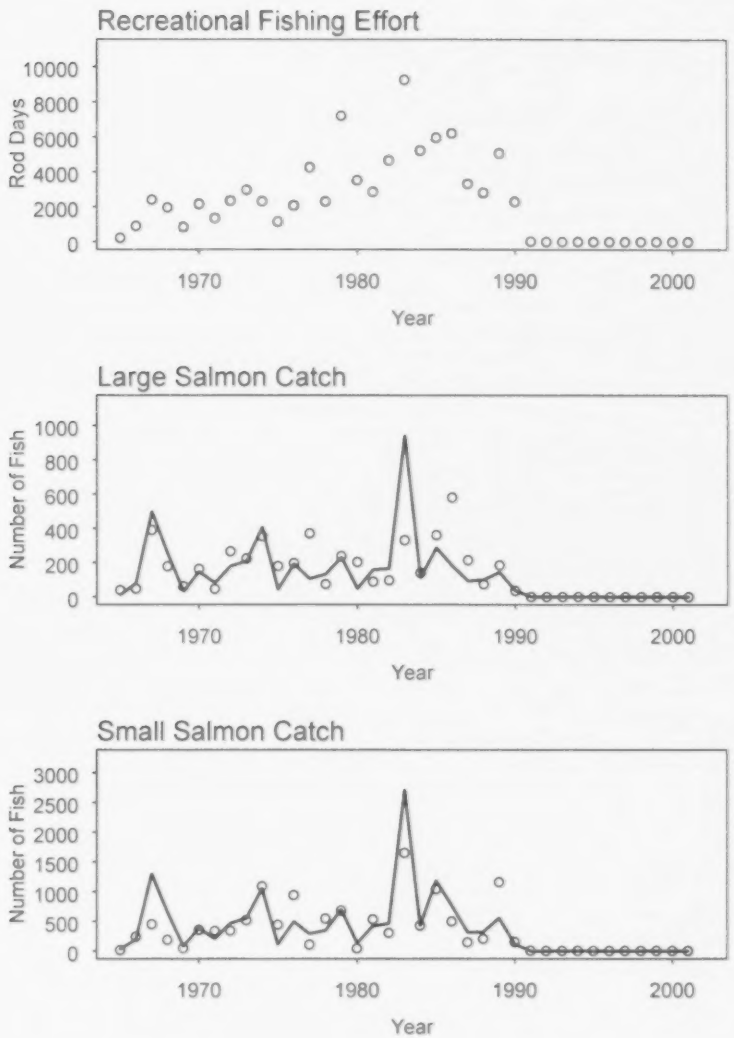

Figure 2. Fishing effort and observed (points) and predicted (lines) Atlantic salmon catches on the Stewiacke River, NS, from 1965 to 2001. The recreational fishery was closed after 1990.

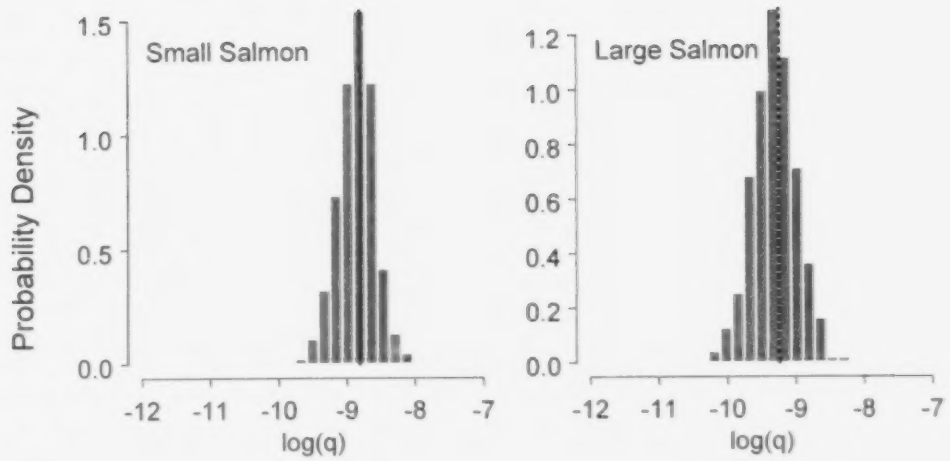

Figure 3. Posterior probability densities for the natural logarithms of the recreational fishery catchability coefficients for small and large salmon. The dashed lines show the maximum likelihood estimates.

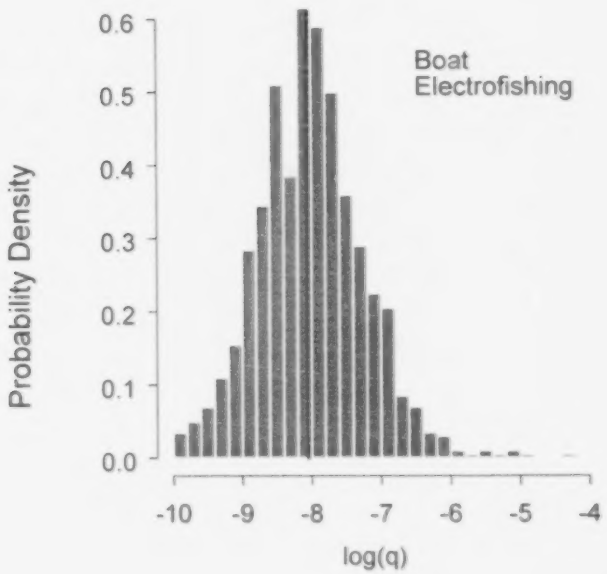

Figure 4. Posterior probability density for the natural logarithm of the electrofishing boat adult catchability coefficient. The dashed line shows the maximum likelihood estimate.

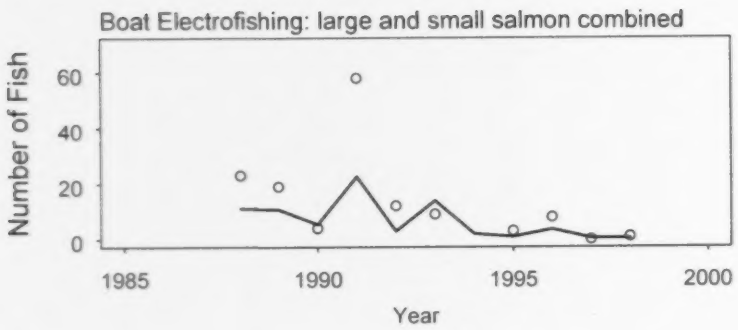

Figure 5. Predicted (lines) and observed (points) catches of adult Atlantic salmon in the Stewiacke River, NS, by electrofishing with a boat from 1988 to 1998.

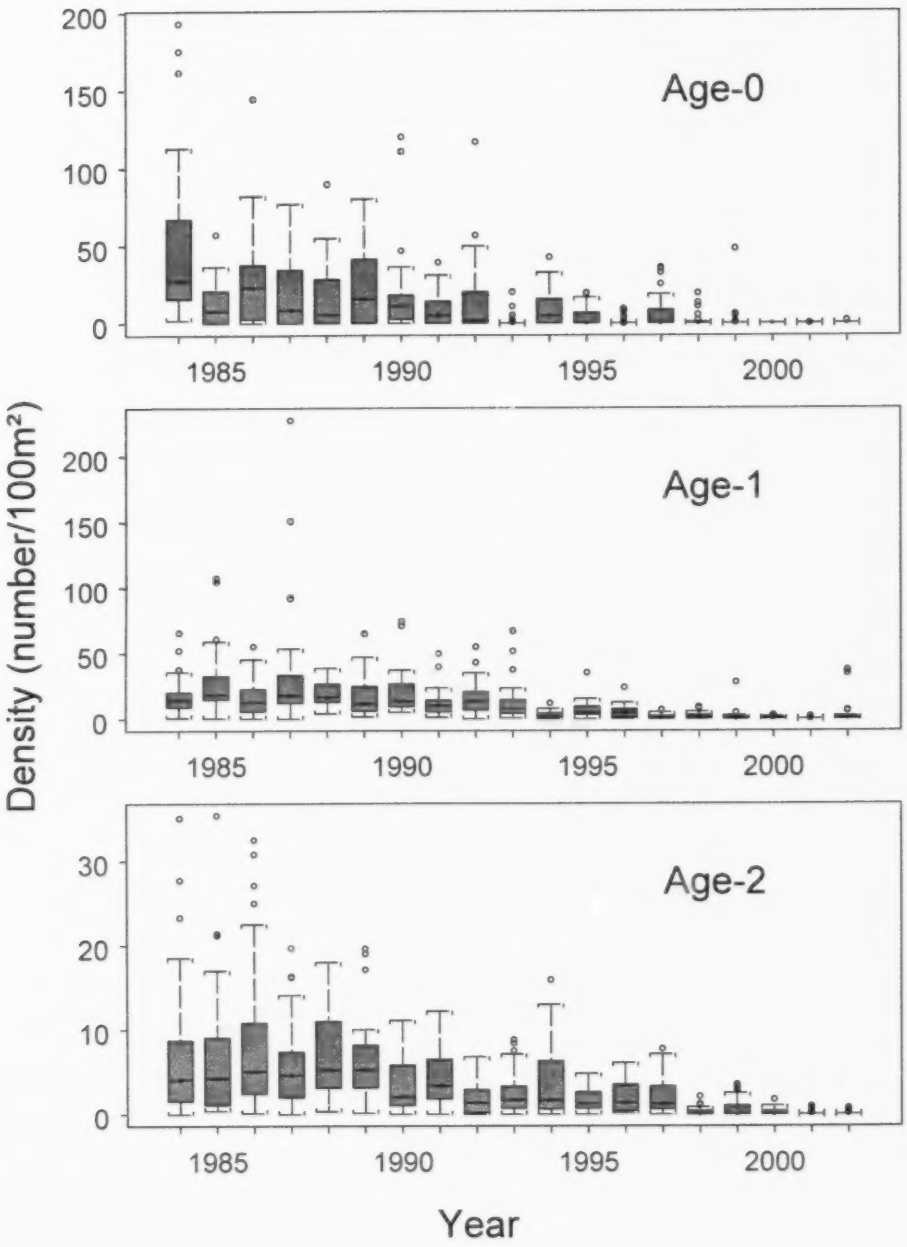

Figure 6. Box plots showing the distributions of densities of age-0, age-1 and age-2 Atlantic salmon in the Stewiacke River, NS, from 1984 to 2002, determined by electrofishing. The box shows the inter-quartile spread and the line in the box shows the median value. Whiskers are drawn to indicate lowest and highest values within 1.5 times the inter-quartile range from the quartile. Outliers are shown as points.

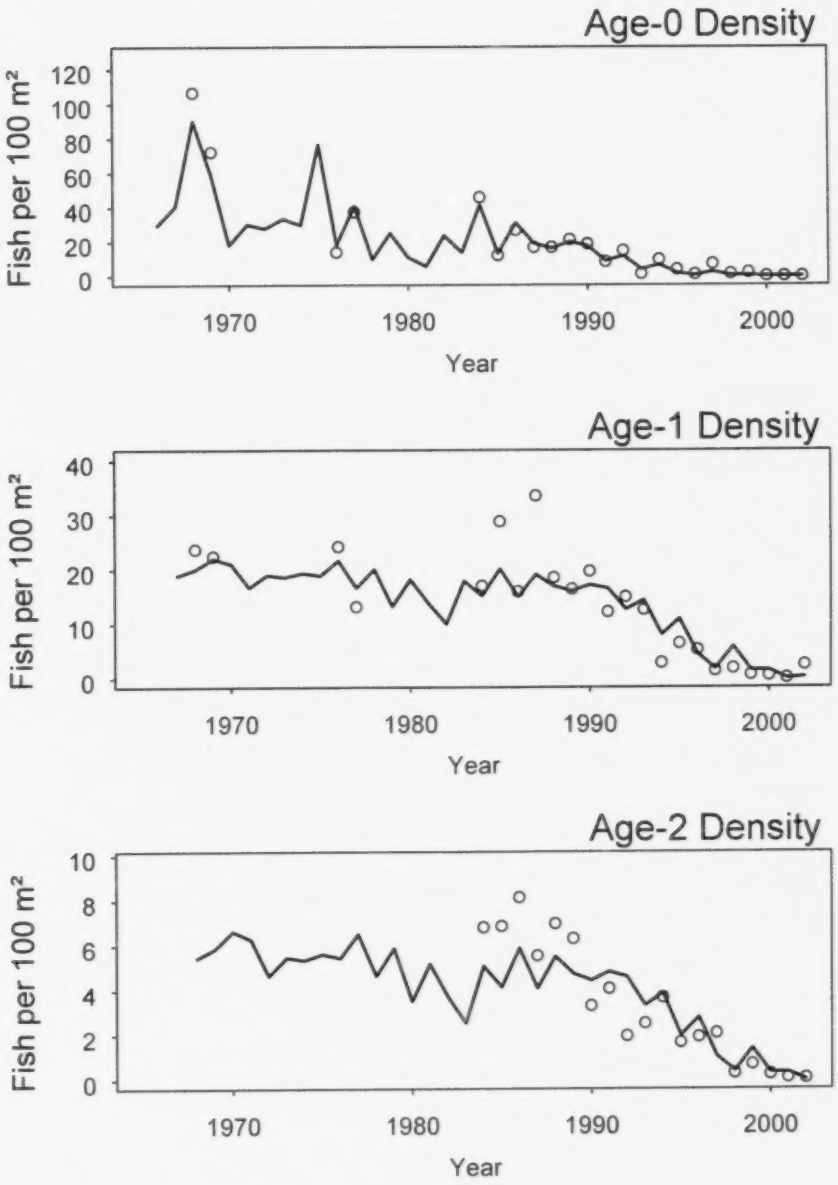

Figure 7. Mean density of juvenile Atlantic salmon in the Stewiacke River, NS, from 1966 to 2002. The points are the observed densities determined by electrofishing. The lines are the predicted densities from the assessment model.

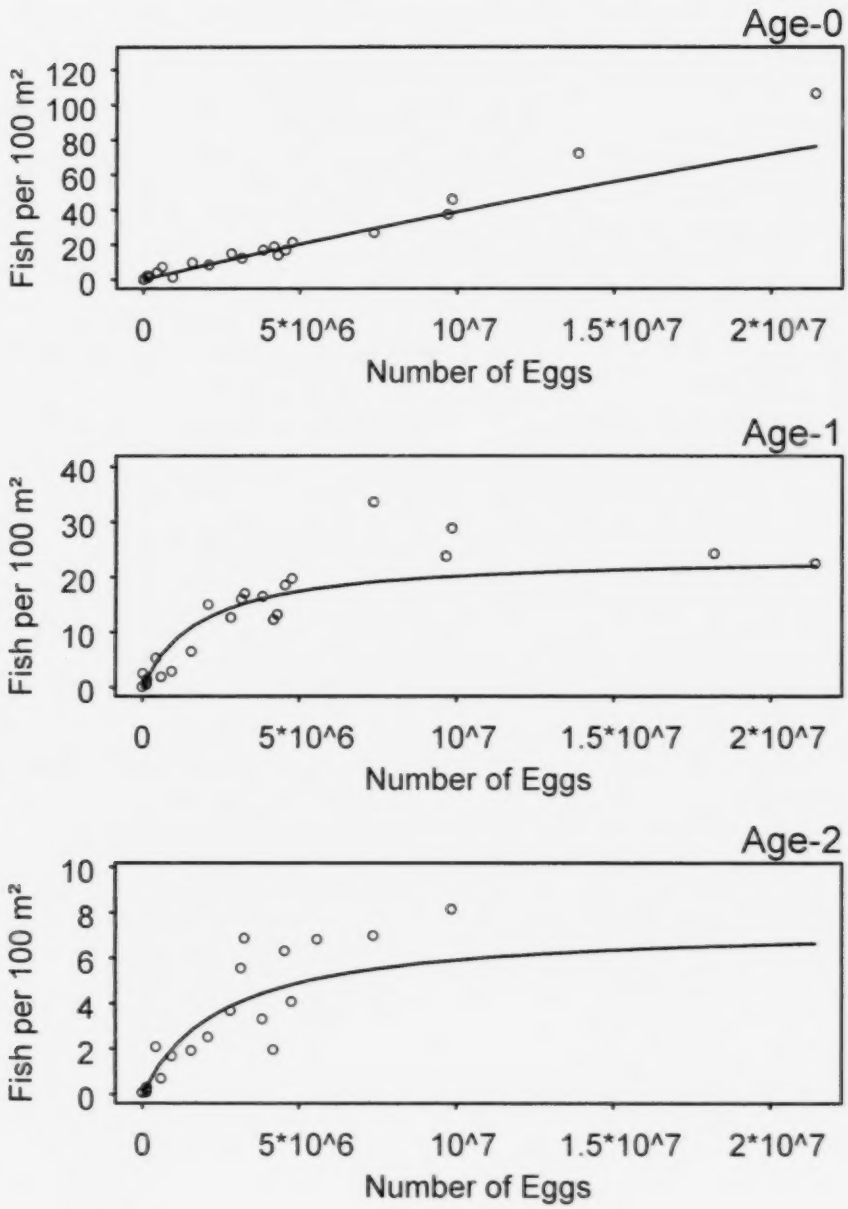

Figure 8. The relationship between egg deposition in year *t* and the number of juvenile Atlantic salmon in years *t*+1 (age-0), *t*+2 (age-1), and *t*+3 (age-2) in the Stewiacke River, NS. Juvenile densities were determined by electrofishing between 1968 and 2002. Egg deposition was predicted using the assessment model.

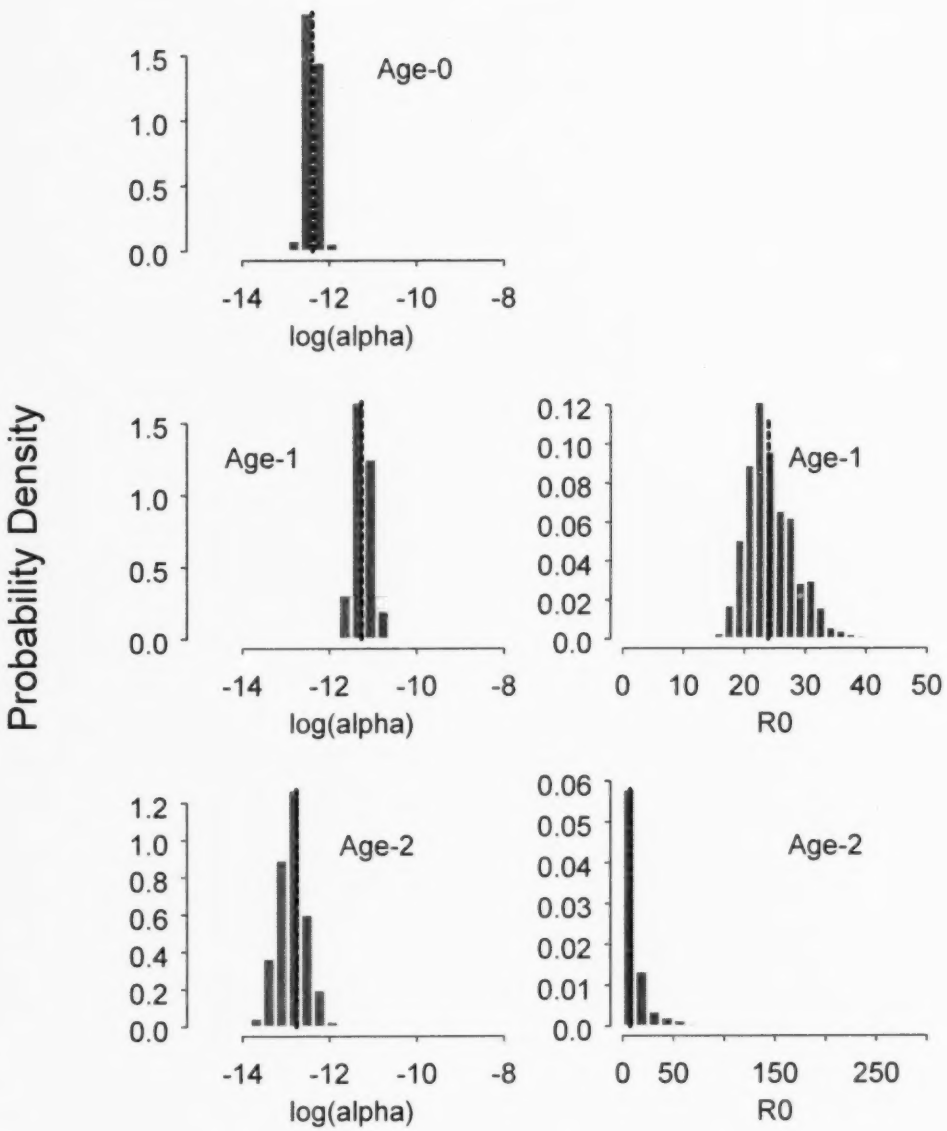

Figure 9. Posterior probability densities for the natural logarithm of alpha and R_0 for age-0, age-1 and age-2 juvenile Atlantic salmon in the Stewiacke River, NS. The dashed lines show the maximum likelihood estimates. The units for alpha are number of fish per egg and the units for R_0 are number of fish per 100 m^2. R0 was not estimated for age-0 salmon.

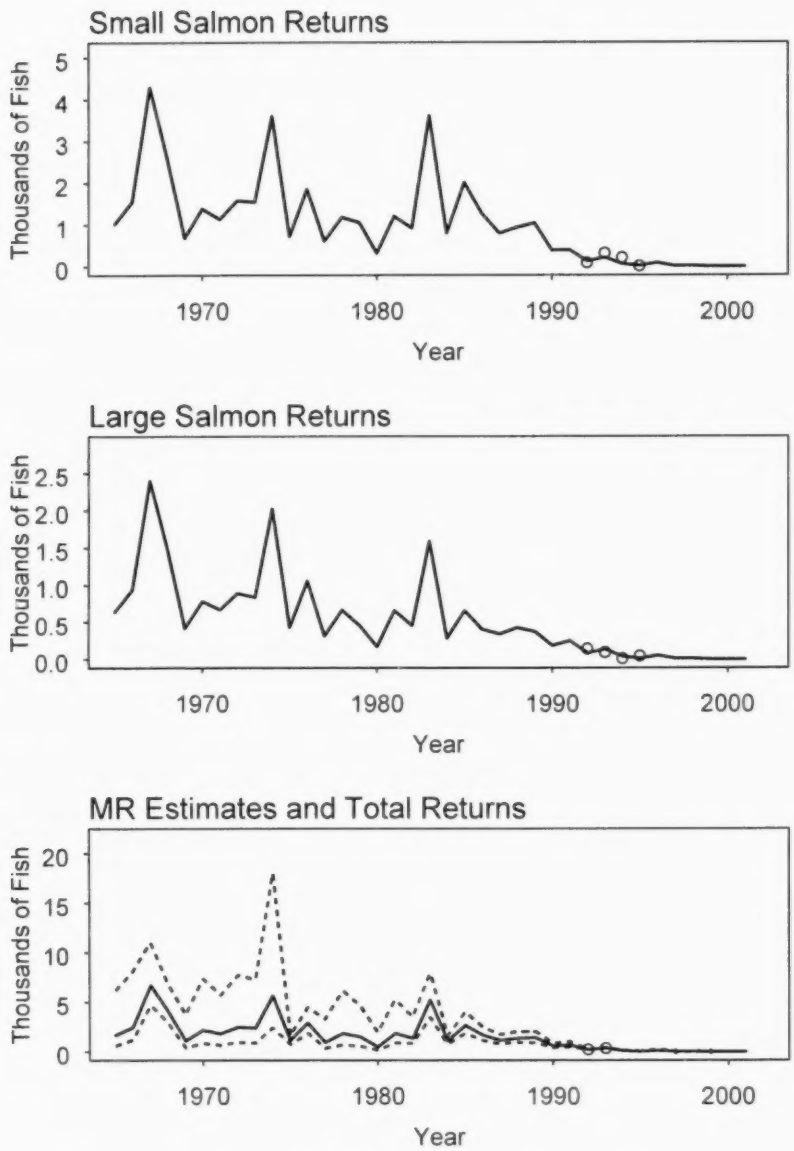

Figure 10. Estimated number of salmon (solid lines) returning to the Stewiacke River, NS, from 1965 to 2001. The points are the fence counts for large and small salmon (corrected for capture efficiency in 1992 and 1993) and mark recapture estimates (total returns). The dashed lines are the 10^{th} and 90^{th} percentiles of the posterior probability density for the total number of salmon returning to the river.

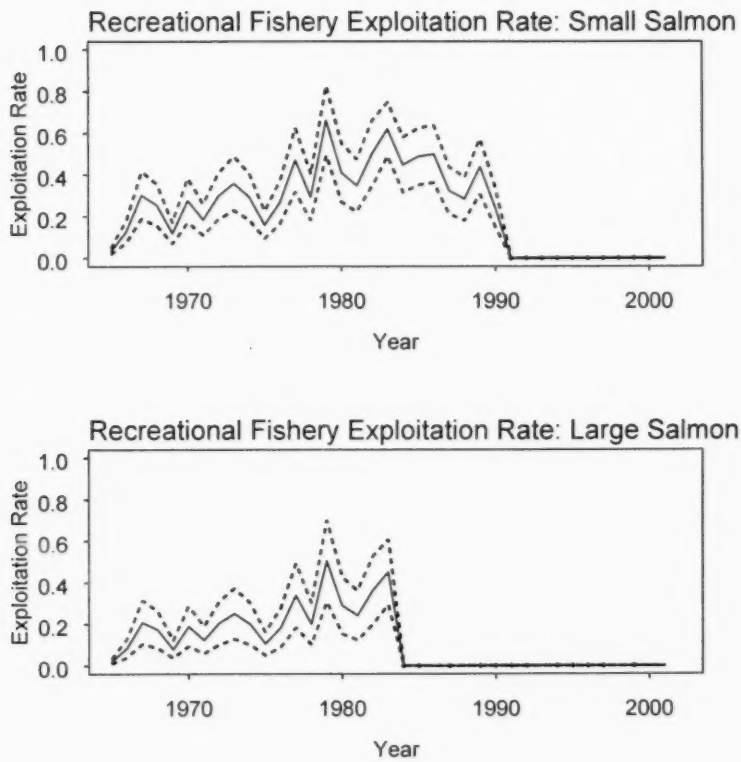

Figure 11. Estimated harvest rates (solid line) for the Stewiacke River, NS, recreational Atlantic salmon fishery from 1965 to 1990. The dashed lines show 95% confidence intervals based on normal approximations. Harvest rates were assumed to be 82.4% and 75.8% the catch rates for small and large salmon respectively based on estimates of the proportion of fish retained by the fishery for the years 1983 - 1990 (small salmon) and 1983 for large salmon. The recreational harvest fishery for large salmon was closed after 1984. The catch and release fisheries were closed after 1990.

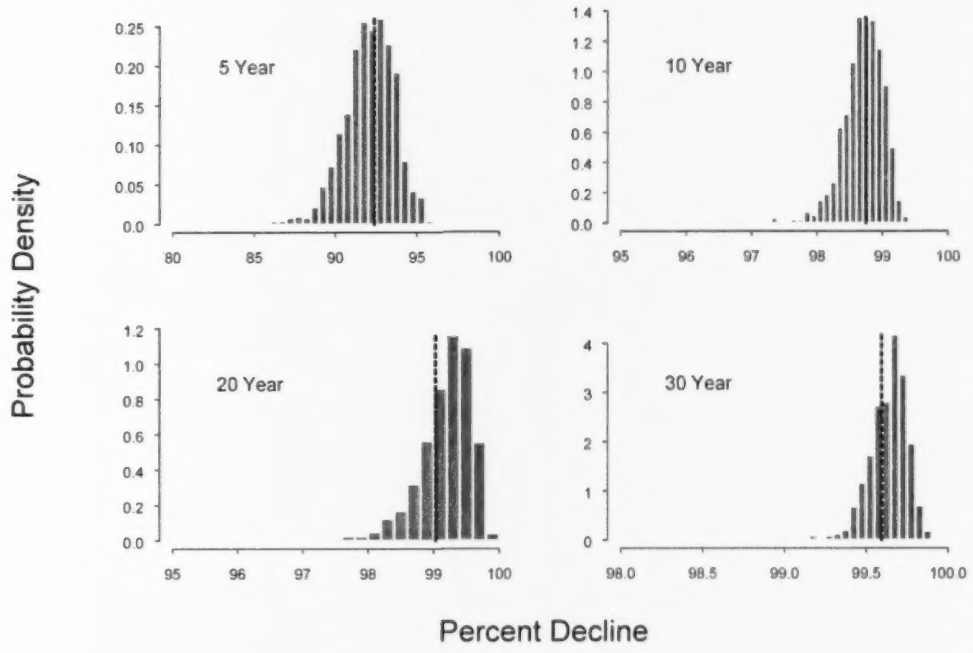

Figure 12. Posterior probability densities for the percent decline in the number of Atlantic salmon returning to the Stewiacke River over a 5, 10, 20 and 30 year time period. Percent decline was calculated by comparing the mean number of returning salmon for the 1997 - 2001 time period to means for the 1992 - 1996 time period (5 year comparison), the 1987 - 1991 time period (10 year comparison), the 1977 - 1981 time period (20 year comparison) and the 1967 - 1971 time period (30 year comparison). The dashed lines show the maximum likelihood estimates for the percent decline.

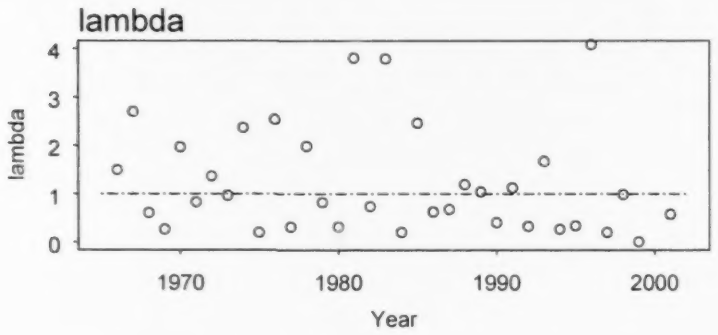

Figure 13. The ratio of N_t to N_{t-1} for Stewiacke River salmon from 1966 to 2001. The dashed line is the level at which the population size does not change.

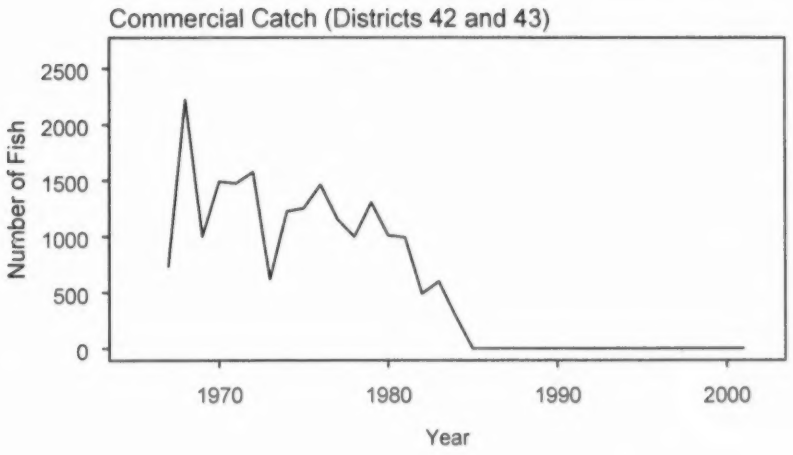

Figure 14. The commercial Atlantic salmon catch in Districts 42 and 43 in Nova Scotia from 1967 to 1984. The fishery was closed in 1985.

Appendix 1. Posterior probability densities for the number of Atlantic salmon returning to the Stewiacke River annually from 1966 to 2001, and the annual recreational catch rates for the 1966 to 1990 time period. The dashed lines show the maximum likelihood estimates.

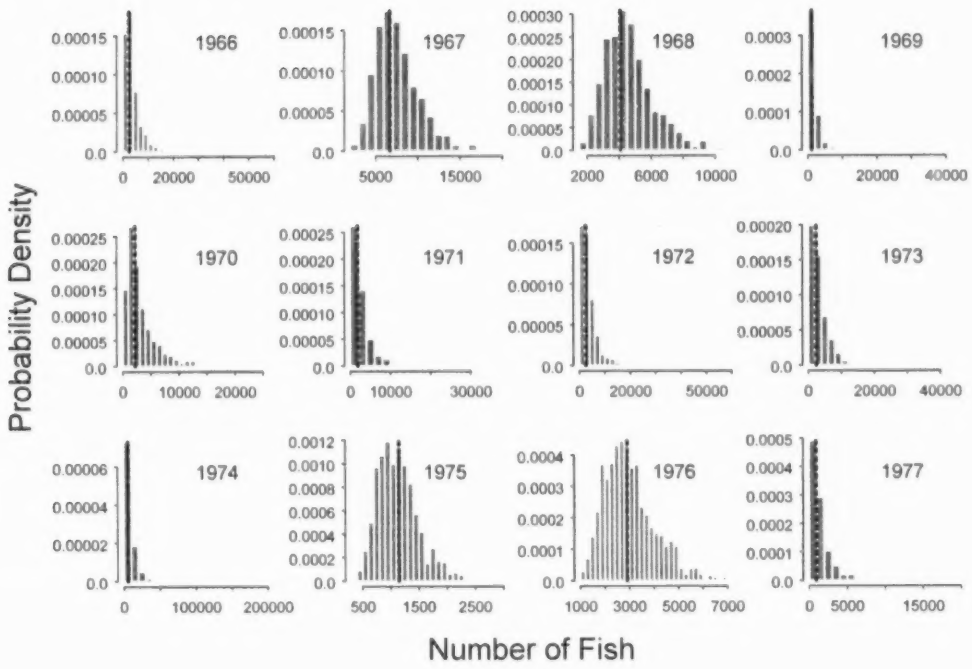

Figure A1.1. Number of salmon returning to the Stewiacke River 1966 to 1977.

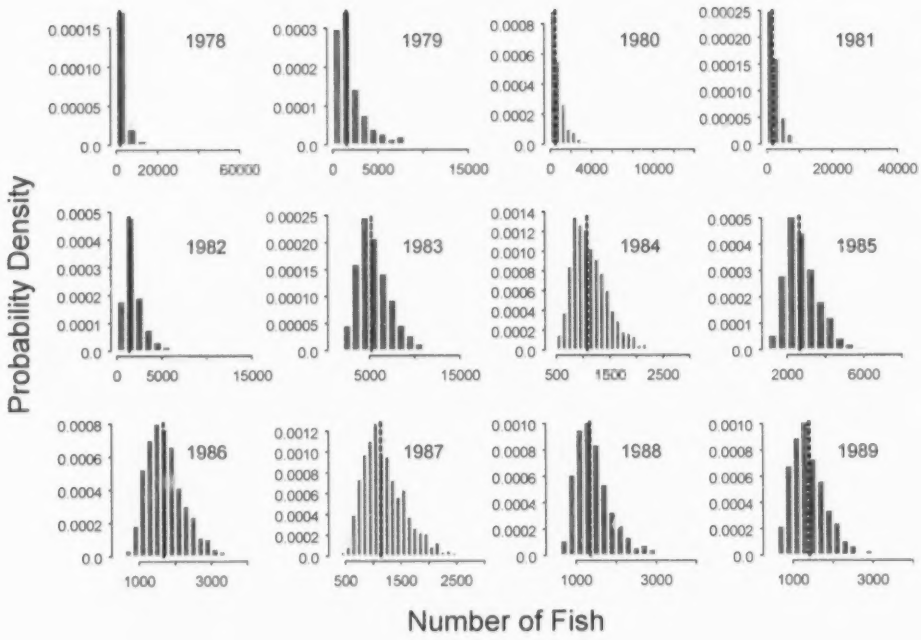

Figure A1.2. Number of salmon returning to the Stewiacke River 1978 to 1989.

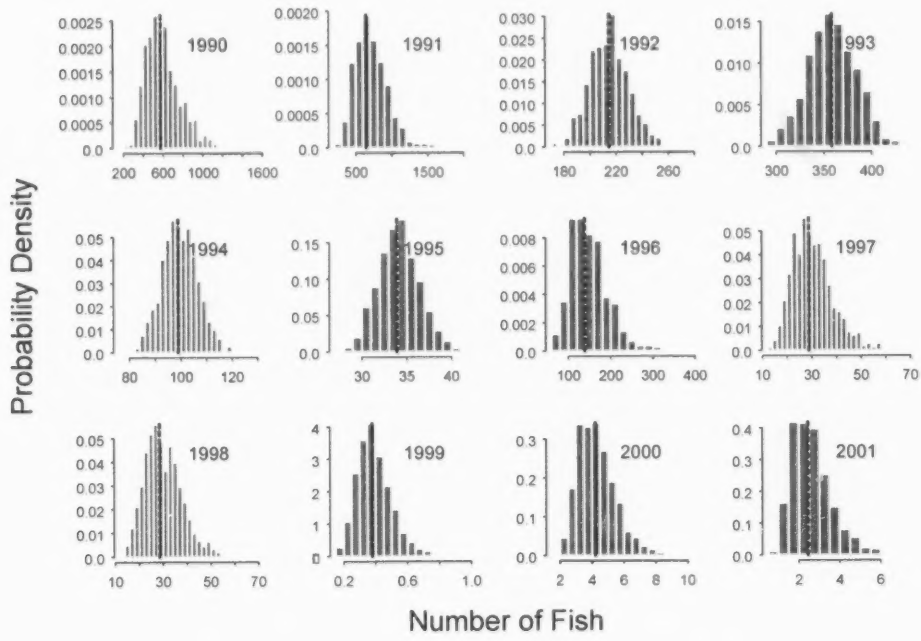

Figure A1.3. Number of salmon returning to the Stewiacke River 1990 to 2001.

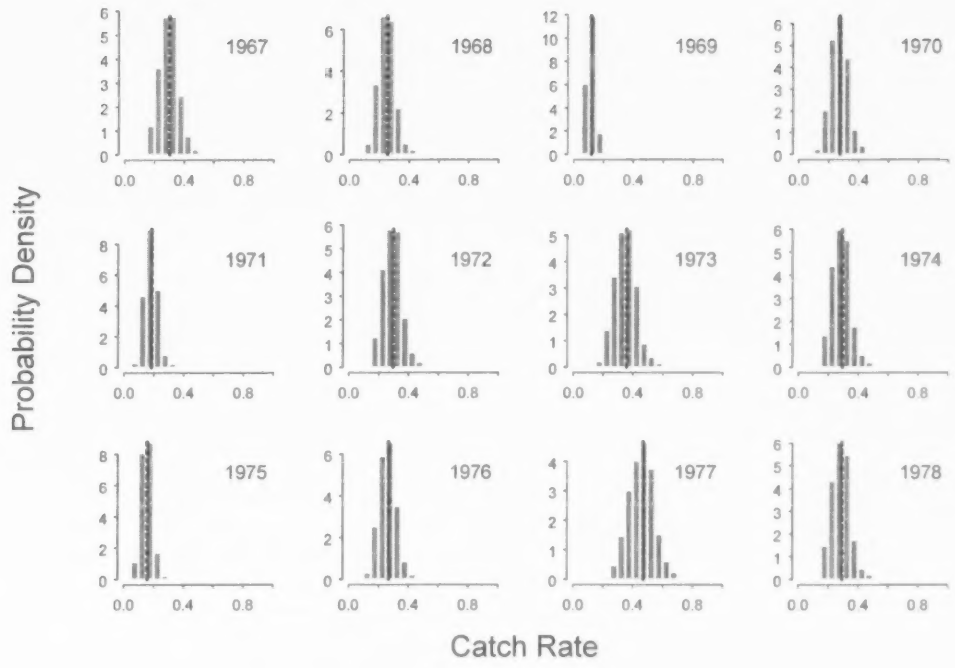

Figure A1.4. Recreational catch rates for small salmon 1967 to 1978.

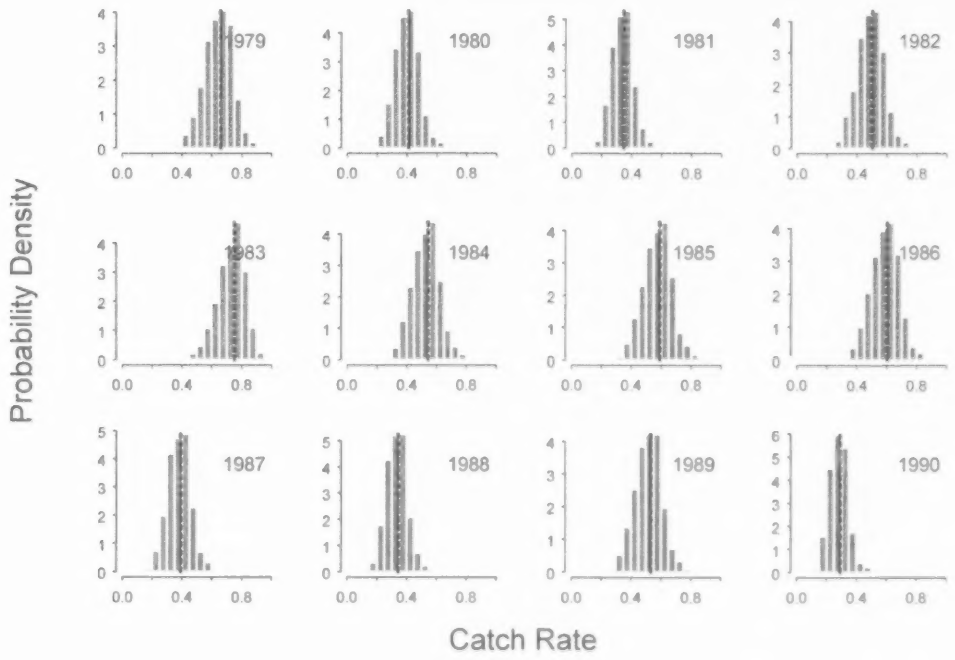

Figure A1.5. Recreational catch rates for small salmon 1979 to 1990.

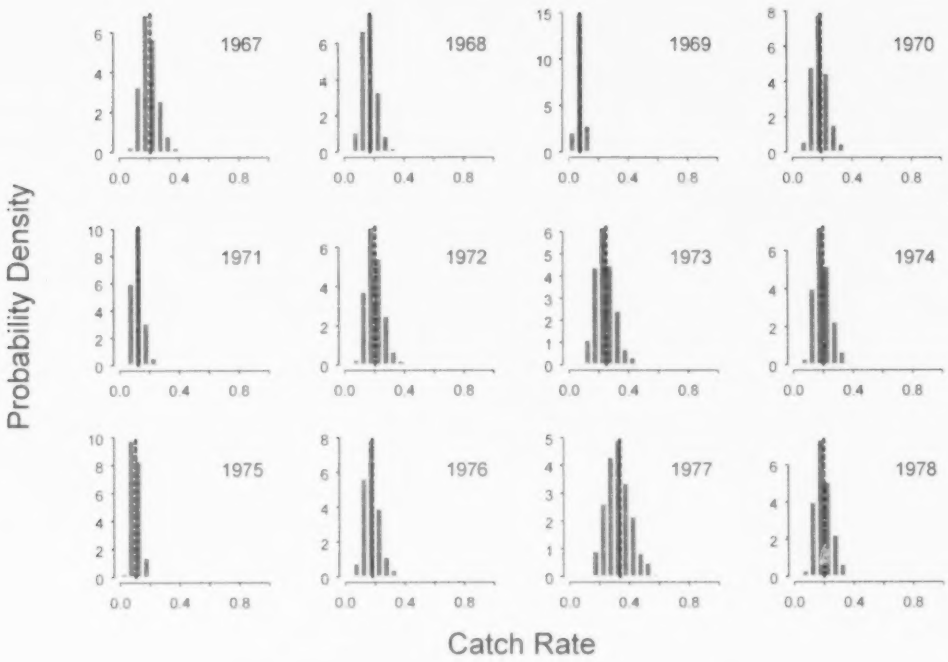

Figure A1.6. Recreational catch rates for large salmon 1967 to 1978.

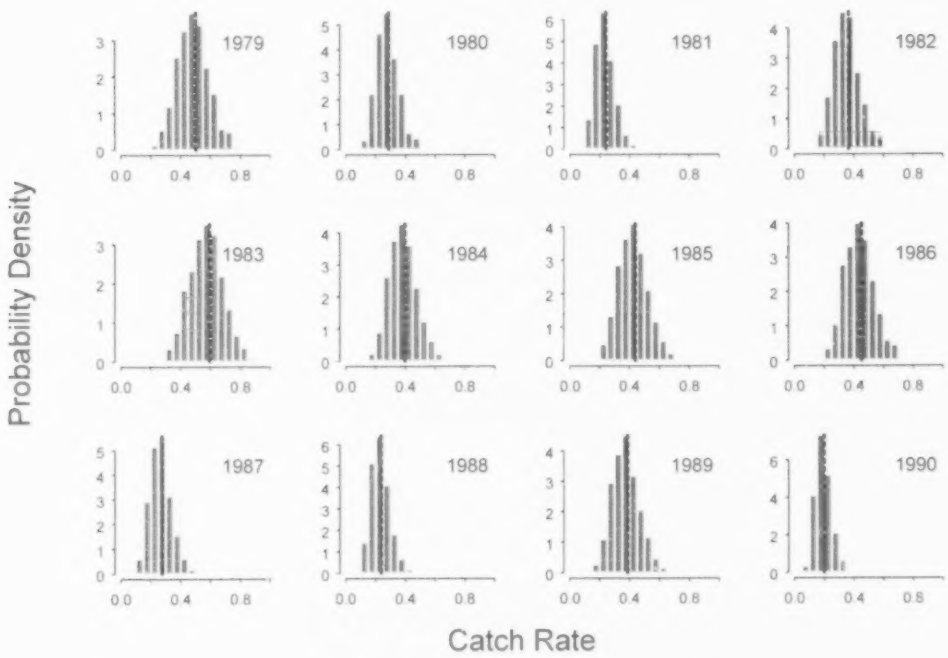

Figure A1.7. Recreational catch rates for large salmon 1979 to 1990.